PETROLEUM TECHNOLOGY ALLIANCE CANADA

PTAC

Alberta Upstream Petroleum Research

Report One:

TESTING PROTOCOLS AND INTRODUCTION

EVALUATION OF NO_x EMISSION ABATEMENT TECHNOLOGY OPTIONS AND BEST MANAGEMENT PRACTICES

Prepared for and with funding by PTAC and the Alberta Upstream Petroleum Research Fund (AUPRF)

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ABSTRACT:

Six reports are produced for operators of stationary natural gas engines. The key message for the reports as identified by PTAC is “What are the technical or process solutions to improve engine life and health, minimize cost and optimize NO_x emissions.” This first report is dedicated to describing the background information that every Engine operator must understand in managing their engines and engine fleets to be compliant with NO_x regulatory requirements. The topics discussed in this report include

- combustion theory,
- the influence of aspects external to the engine,
- regulatory requirements,
- emission testing requirements,
- challenges and considerations for testing engines with different combustion styles
- best management practices for testing, and
- managing testing programs for engine fleets.

Engines that are configured in a lean burn combustion style will require less frequent testing and lower effort in maintenance and operating expense than engines configured in a rich burn configuration. Rich burn engines require a catalyst to meet NO_x regulatory requirements. Lean burn engines will likely comply with NO_x regulatory limits without additional emissions treatment and provide the added benefit of about 15% less fuel consumption than the same engine model configured for rich burn combustion.

Fleet management testing programs can add value to the operator by accessing economies of scale from an alliance with a qualified testing agency. Many testing agencies are available but the equipment utilized and the methods employed require qualification. In house testing programs may also be adopted.

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1. Introduction and Study Scope

Operators of stationary natural gas fired engines in the oil and gas sector are regulated by increasingly restrictive limits on nitrogen oxide (NO_x) emissions. These regulations require mandatory testing and mitigation of fleet emission levels over time. The regulations are established by Environment Canada. This study is limited to natural gas fuelled, four stroke, stationary engines in oil and gas industry service. The 30 most common engine models larger than 75 kW are considered. These engine models will be discussed in detail along with technology options for meeting NO_x regulatory compliance.

Appendix A lists the engines and components that are both considered and excluded from the scope of this study. The most popular models considered are listed with their combustion style. We have also listed the ignition system and engine management systems that are considered. Unpopular ignition and engine management systems that are not considered are also listed. Finally, we list the engine models that comprise less than 5% of the Alberta fleet that are not considered. Appendix C lists the history of the most popular engine models to show that models with the same name are different over time.

Appendix B lists the features and capability of the popular ignition system models. The reader will note that a wide range of sophistication exists. The features available will dictate how adaptive the ignition system can be.

Engine manufacturers and other manufacturers have developed technology solutions to achieve compliance with the regulations. Engines are complicated and the selection of solutions are numerous with varying degrees of effectiveness. Operators are faced with allocating significant resources and effort to qualify the solutions and testing requirements in order to ascertain the optimum equipment configuration. Working through the process and the budget implications takes years. Our Best Management document will allow operators to examine the options available for their particular engine model and the life cycle costs associated with the options. Supporting information on testing, regulations and combustion theory are also presented to better understand the effectiveness of the solutions.

The key message for the reports as identified by PTAC is "What are the technical or process solutions to improve engine life and health, minimize cost and optimize NO_x emissions". The following list identifies the six reports that encompass the scope of the study.

- Report 1: Testing protocols and Discussion of factors affecting emissions
- Report 2: Pre-chambered lean burn engine models
- Report 3: Open chamber lean burn engine models
- Report 4: Stoichiometric engine models with and without catalyst
- Report 5: Engine models comprising less than 5% of the fleet
- Report 6: Trends and Management Practices

This introduction will be provided in each of the six reports to provide the reader with context. It will also allow the reader to identify the report that contains their area of interest without navigating the other topics. The presentation of the topics is designed with lists, tables and graphs to illustrate the data and minimize the use of explanatory text.

2. Engine and combustion fundamentals including the influence of variables

The basics of engine operation with consideration to fuelling and emissions, and how those interrelate to combustion are discussed in the following sections.

2.1. Combustion and air-fuel ratios

Combustion is the chemical reaction between fuel and oxygen that releases energy. Ideal combustion of a hydrocarbon results in CO_2 and water and energy as the only products of combustion. Incomplete combustion however, can have a number of by-products, including CO, NO_x, hydrocarbons and many other chemicals. The ratio of air to fuel is therefore very important to an engines operation, efficiency and emissions.

The air- fuel ratio can be expressed on either a volume or mass basis. If volume is used, then the conditions of temperature and air pressure must be specified. Testing corrections are required if conditions do not match the standard. If a mass basis is employed for measurements then corrections are not needed.

The chemically correct, or ideal air fuel ratio is called the stoichiometric ratio, and assumes perfect combustion using all the available fuel and oxygen in the air. The fuel used by the engines studied in this report is natural gas. This is primarily methane, with small amounts of other gasses, such as ethane and propane. The stoichiometric air fuel ratio for pipeline quality natural gas is approximately 15:1 on a mass basis. The ideal combustion reaction of methane in air is as shown in the chemical formula below. Argon contributes less than 1% and is ignored by Caterpillar and Waukesha.

$$CH_4 + 2O_2 + 7.55(N_2\text{+Ar}) = 2H_2O + CO_2 + 7.55(N_2\text{+Ar})$$

Real combustion however, often isn't perfect, so the air fuel ratio is generally not exactly at the stoichiometric ratio. An operating regime with excess air relative to the amount of fuel is called lean and with an excess of fuel is called rich. Maximum power is produced at 10-15% rich mixtures. Minimum fuel consumption is produced at 10-15% lean mixtures. Waukesha's engine fuel consumption ratings are normally stated as "best Power" or "best fuel" to indicate the air fuel ratio for each setting. These rating do not apply to lean burn combustion styles because only one setting will be specified. Engines equipped with NSCR catalysts require air fuel ratios richer than stoichiometric in order to provide fuel for combustion in the catalyst. Engines that run leaner air fuel ratios can avoid the use of NSCR catalyst to meet regulatory NO_x emissions. Some engines equipped with pre-chambers to ignite ultra lean mixtures are designed to reduce both fuel consumption and NO_x emissions to meet regulatory limits.

Figure 1 below shows the relative behaviour of the combustion products as the air fuel ratio changes from rich to lean. It is important to note that some emissions like unburned hydrocarbons (HC) increase as the fuel concentration is moved away from stoichiometric in either the rich or lean direction. The Y axis suggests the relative concentration of each of the components rather than the relative magnitude of each component's contribution to exhaust emissions.

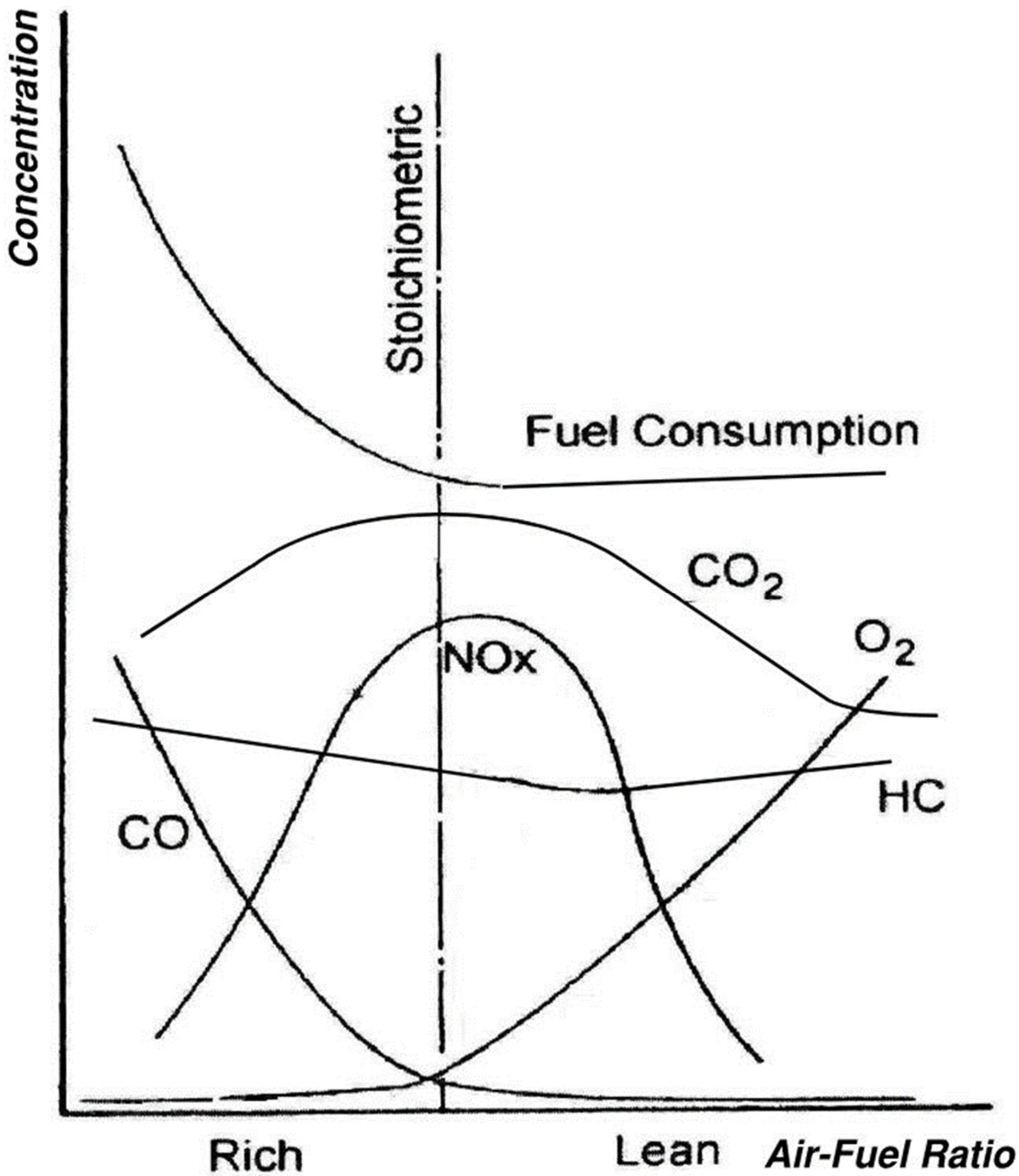

Figure 1 Relative behaviour of combustion elements with respect to air fuel ratio

One strategy proposed for NO_x reduction is to run the engine ultra rich. Running at very rich air fuel ratios does reduce the formation of NO_x. It also reduces the available power and dramatically increases the fuel consumption, the formation of CO and the volume of unburned hydrocarbons. The partially burnt fuel also produces soot that contaminates the crankcase oil and fouls spark plugs. If the engine is equipped with a catalyst, the unburnt fuel from the engine will need to be burned in the catalyst, which produces large quantities of heat. This poses a risk of fire or melting the catalyst which is a very expensive item to replace. Tuning an engine ultra rich is a practice that is not approved by any engine manufacturer and is not recommended. Operating the engine very rich also creates a safety hazard by promoting conditions for explosions in the intake and exhaust manifold.

The concentration of pollutants in exhaust emissions can be measured in a variety of units. The common measurement scales are parts per million (PPM), grams per BHP-h, grams per kW h or percentage. Waukesha offers a simplified conversion method using approximate factors for each engine series (see Waukesha publication S-8483-6). The following formula is universally applied to convert the measurement units.

Volume = Vp x 10^6 ÷ (Ve)

Volume = dry volume in units of ppmvd

Vp = Volume of pollutant = emission factor (g/bhp-h) x horsepower x (1/molecular weight) x molar volume x conversion factors

Ve = volume of exhaust= F-factor for exhaust volume x excess air correction x engine brake specific fuel consumption x horsepower x conversion factors

2.2. Aspiration

One factor affecting the engine operation is the temperature of the incoming air. Hot air is less dense than cool air. Hot air provides less oxygen per unit volume drawn into the cylinders to support combustion. The net result is a reduction in produced power. Hot air temperatures also promote detonation. A naturally aspirated engine allows the combustion air to flow directly into the cylinders without intermediate cooling. A turbocharged or supercharged engine is different.

Turbocharging is a method where energy is recovered from the exhaust gas stream to turn a compressor, which in turn compresses the incoming air to a higher pressure than ambient. The compressor increases the density of the combustion air. Increasing the air volume and pressure provides more oxygen to mix with a larger amount of fuel to make more power. A turbocharger can make the thermodynamic cycle more efficient by recovering energy from the exhaust stream that would otherwise be discharged into the atmosphere. Supercharging also compresses the combustion air. A supercharger is directly driven from the crankshaft of the engine. An intercooler is required to cool the compressed air.

Compressing air produces heat. An intercooler is employed to cool the air after it is compressed and prior to it being admitted to the cylinders. The intercooler is a shell and tube heat exchanger. It transfers the heat from compressing the combustions air into the auxiliary water circuit of the engine cooling system.

Supercharging is preferred when loads are constantly changing or when a fast engine response to load changes are needed. A fast response to increasing power demands are possible because the supercharger is driven directly from the engine. Turbocharging offers a delayed response to changing engine load because it takes time for the exhaust gas volume to increase and subsequently increase the turbochargers' impeller speed to compress the air. This phenomenon is called "turbo lag".

2.3. Fuel Gas

Fuel gas for a spark ignited natural gas engine is primarily methane (CH_4) with smaller percentages of heavier hydrocarbons ranging from ethane (C_2H_6) to heptane (C_7H_{16}). Gases such as carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), nitrogen (N_2), helium (He), hydrogen (H_2), and hydrogen sulfide (H_2S) may also be present. The relative concentration of the various components changes with the sources of the fuel gas. Fuel gas is provided from the produced gas at each facility or purchased from a utility. The Utility defines the standard of quality for the fuel gas it sells and that will vary by location. The quality of fuel gas produced from produced gas will vary with the level of processing and the variable quality of the produced gas.

Engine manufacturers have defined pipeline quality natural gas as the reference fuel. Both Waukesha and Caterpillar have extensive specifications for the fuel gas. They require a site specific fuel gas analysis to be performed to ensure fuel compatibility with the engine. Important characteristics are the heating value and knock index. Two important numbers are the Lower Heating Value (LHV) and the Higher Heating Value (HHV). Both values are a measure of the amount of useable energy in a specified amount of gas.

The LHV is a dry gas and the HHV is the same gas with the latent heat of vaporization added to the LHV. Standard industry practice is to saturate the dry gas to estimate the HHV when the amount of water vapor in the gas is unknown. The units are either British Thermal Units per standard cubic foot (BTU/scf) or mega Joules per normal cubic meter (MJ/m^3). Typical pipeline quality gas in Alberta is approximately 900 BTU/scf.

The fuel gas composition will determine a value known as the knock index, which is somewhat analogous to the octane rating for gasoline. The knock index defines the power rating for the engine. It also serves to identify the suitability of the fuel composition to preserve engine health. The minimum fuel quality specified will avoid pre-ignition and detonation. Both pre-ignition and detonation can cause severe engine damage.

2.4. Pre-ignition and Detonation

Pre-ignition is when the air-fuel mixture in the cylinder ignites without, and before, the spark plug firing. Often this is caused by hot carbon deposits, hot sharp edges of a valve or hot surfaces on a spark plug. Carbon deposits in the combustion chamber from leaky oil seals are a typical source. Pre-ignition provides a short duration pressure spike that occurs because the piston is at top dead center and cannot move downwards when the combustion event occurs. Exceedingly high pressure spikes result. Pre-ignition promotes catastrophic failures in very little time.

The normal combustion process expects the spark plug to ignite a flame that rapidly sweeps across the entire combustion chamber. The flame front produces a combustion-induced temperature and pressure rise that separates the burning air-fuel mixture from the unburned mixture. The flame front is initiated by the firing of the spark plug prior to the top dead center travel of the piston and continues to sweep across the combustion chamber in milliseconds until it consumes the entire fuel-air charge. Pressure in the cylinder is managed in a controlled fashion by the downward travel of the piston while the burning gasses are expanding.

Detonation is a much more complex phenomenon normally caused by auto ignition in the combustion chamber. Detonation occurs when the flame front propagates across the combustion chamber and the unburned air-fuel mixture (called the end gas) is compressed ahead of the flame. Some of the end gas air-fuel mixture may undergo chemical reactions prior to normal combustion. The products of these reactions may then undergo spontaneous autoignition resulting in an explosion rather than a controlled ignition. Pressure spikes result from detonation but not to the same magnitude as in pre-ignition. Engines may continue to operate with detonation for extended periods if the pressure spikes are low enough. However, detonation is known to initiate pre-ignition. Detonation is affected by compression ratio, intake manifold pressure, ignition timing, combustion air temperature, combustion air humidity, fuel gas composition, engine load and air-fuel ratio. A discussion of these variables is beyond the scope of this report.

2.5. Post Ignition

Post ignition may result from carbon buildup in the combustion chamber that remains above the auto ignition of the fuel combined with a remaining source of fuel in a stoichiometric mixture. Operating the engine in a very rich regime is normally required for the appropriate circumstances to combine for this event. The typical definition for post ignition describes an engine that continues to operate after the ignition is shut off. This phenomenon is known as run-on.

Another situation arising in post-ignition is when fuel in a stochiometric mixture is present in the cylinder when the exhaust valve is open. Products of combustion are expelled into the exhaust line. Fuel in a stoichiometric mixture might also be present in the exhaust line due to valve overlap or an engine that won't start with fuel pumping through the engine. Uncontrolled combustion in either the cylinder or the exhaust line can result in an explosion. The event is often called a backfire. Technically this term is incorrectly applied as uncontrolled combustion can occur in the exhaust line or the air intake line. A combustion event in the exhaust line can rupture the exhaust line. Explosions in the air inlet line or intake manifold normally require pre-ignition or detonation at the time when the intake vale is open.

2.6. Contaminants

Natural gas is classified as sweet or sour. Sour gas contains hydrogen sulfide (H_2S). The amount of sulphur permitted in the fuel gas by engine manufacturers is very small. Waukesha specifies less than 50 µg/BTU for most models. Caterpillar defines the allowable concentration according to the application and the type of engine. Consult Caterpillar's specifications for the specific engine model.

Contaminants in the fuel are compounds such as free water, various non-combustible gases, and siloxanes. Siloxanes are common constituents of landfill gas and are generally found is things such as shampoos and soaps. Siloxane compounds create hard, glass like deposits on internal engine components. Very low concentrations will contaminate sensors and catalysts. Siloxane compounds in the fuel are to be avoided. In general, engine manufacturers recommend that the fuel gas be treated to eliminate contaminants.

High energy component fuel gas is a gas that has a high percentage of components with a higher heating value. The most common examples of gas components in a fuel gas mixture with higher heating value are ethane and propane. The engine will require adjustment of the timing to run on hotter fuels and that may be associated with a lower power rating. The typical fuel gas specifications for a Waukesha engine is shown in Table 1.

WAUKESHA STANDARD COMMERCIAL QUALITY NATURAL GAS COMPOSITION	
Methane content	93% by volume minimum
Non-combustible inerts (N_2, CO_2, He, etc.)	3% by volume maximum
Non-methane hydrocarbon mass fraction	0.15 (15% by mass) maximum
Liquid hydrocarbons (Typically C_5+)	None
Oxygen	0.2% by volume maximum
Water vapor	100% relative humidity
PERFORMANCE CHARACTERISTICS	
Lower Heating Value	916 BTU/scf (60° F, 14.696 psia) [approx. 36.01 (0° C, 101.325 kPaa) MJ/Nm^3]
Saturated lower heating value	900 BTU/scf (60° F, 14.696 psia) [approx. 35.38 (0° C, 101.325 kPaa) MJ/Nm^3]
Waukesha Knock Index	91 minimum
Stoichiometric air/fuel ratio	16.08:1 by mass, approx.
Hydrogen/carbon ratio	3.85:1 approx.

Table 1 Commercial Fuel Gas Composition

Each engine will have minimum specified fuel flow and pressure to develop full horsepower. The minimum requirements for each application are required to maintain engine health. Each engine manufacturer must be consulted to determine the requirements for their engine model.

2.7. Ignition Timing

Ignition timing is the point at which the sparkplug is fired relative to the crankshaft's position before top dead centre (TDC). The sparkplug is fired before TDC, because of the time it takes to initiate combustion in the cylinder and for the cylinder pressure to rise. This timing point is usually set with an initial base setting for starting and idle, sometimes called static timing and it can be set with the engine not running.

As the engine speed increases, the timing needs to be set earlier relative to TDC to ensure that peak cylinder pressure take place at the correct place in the engine cycle. The reason is that while the fuel takes approximately the same time to ignite, the crankshaft is turning faster, so takes less time to go from the statically timed point to TDC. In the past this timing adjustment was done mechanically with weights and springs, similar to a centrifugal governor. Now the timing is achieved with a computer module and various sensors on the engine that can measure parameters such as engine speed, crankshaft position, camshaft position and the presence of detonation.

The timing has an optimum setting, and this is affected by factors such as the air-fuel ratio, fuel quality and intake air temperature. Deviations from the ideal setting will usually result in reductions in output power. Two abnormal forms of ignition are pre-ignition and detonation, as discussed above. Both of these conditions will reduce the engine power and have the potential to cause serious engine damage.

2.8. Speed Control

The engine speed is controlled by a governor, which can be either mechanical or electronic. The electronic versions can be simple speed controllers, or part of a more extensive engine management system. The governor is a device that maintains a desired engine speed in response to changes in loading. It is somewhat similar to a cruise control system in an automobile. A major property of a governor when selecting one is droop. This describes the relationship of engine speed change from no load to full load in steady state operation. Typical droop ranges are between 0-12%. The intended service will determine the governor type and accuracy needed, for example electrical generation systems require a constant speed to maintain the electrical frequency, so they must maintain 0% droop. Mechanical drive applications, such as a compressor are much more tolerant of speed variations, so the accuracy isn’t as critical. Many factors will affect the throttle response, such as the engine size, driven equipment rotating inertia, and in compression applications the pressure and flowrate of the gas, as well as the number of stages of the compressor. Governor selection and control strategy must be developed by a qualified Engineer.

3. Regulatory Requirements

The Multi Sector Air Pollutants Regulation (MSAPR), SOR/2016-151, is a federal regulation under the Canadian Environmental Protection Act. It regulates NO_x emissions from boilers and heaters, stationary spark-ignited engines that combust gaseous fuels in certain regulated facilities. The regulations apply to various industry sectors. The provinces are tasked with enforcing the regulations. Each province follows the MSAPR regulations although measurement methods and enforcement may vary from one to the next.

3.1. Alberta

Alberta Energy Regulator (AER) is a body of the Alberta Provincial Government whose purpose is to protect public safety, the environment. The AER is Alberta’s sole regulator of the energy industry., AER works with energy companies to ensure compliance with regulations on new and existing facilities. The AER is involved at every stage of an energy project's life cycle. The AER is responsible for regulating the infrastructure required to produce, mine, process, and move all those resources to markets. The infrastructure under their purview includes pipelines, wells, processing facilities, bitumen upgraders, oil sands mines and coal mines.

The AER does the following.

- Review applications and make decisions on thousands of proposed energy developments each year.
- Oversees all aspects of energy resource activities in accordance with government policies.
- Regularly inspect energy activities to ensure that all applicable requirements are met.
- Penalize companies that fail to comply with regulatory requirements.
- Hold hearings on proposed energy developments.
- Continuously look for ways to improve the regulatory system so that it is
  - efficient,
  - adaptive to the global market and technology changes that affect the industry, and
  - demonstrates Alberta's competitiveness.

The Federal regulation, MSAPR, defines the testing protocols for NO_x compliance in Alberta. MSAPR requires a combination of "performance tests" and "emissions checks" at regular intervals. A "performance test" is more detailed and requires three, 20 minute test runs to measure NO_x, O_2, and CO exhaust components according to methodologies outlined in the regulation. An "emissions check" is simpler to execute and conducted with the use of an electrochemical analyzer. MSAPR specifies sample port locations and options for sampling and testing methods.

The MSAPR regulation references several EPA methods as well as ASTM D6522-11. The AER and AEP (Alberta Environmental Protection) specify the provincial testing requirements in Alberta for a variety of equipment types and facilities. Sampling methods and requirements are defined in the Alberta Stack Sampling Code (ASSC), 1996 edition for many emission sources, including stationary natural gas fueled engines. Maximum NO_x emission levels for stationary natural gas engines have not been adjusted as a provincial regulation since the 1996 edition.

3.2. British Columbia

Three test runs are performed to analyze NO_x, CO & VOC emission levels and exhaust flow according to methodologies outlined in the EPA 40 CFR 60 (A) Protocol and following the procedures detailed in the British Columbia Field Sampling Manual, 2003. Each of the three test runs consist of readings taken every 15 seconds for 60 minutes. Standard Conditions for these air quality tests are done at reference conditions of 20°C and 101.325 kPa as per Appendix 9.1, Section 6 of the BC Field Sampling Manual. The applicable EPA test methods are listed in Table 2.

Method	Title	Parameter	Description	Reference
EPA 40 CFR 60 (A) Method 3A	Determination of Oxygen and Carbon Dioxide Concentrations in Emissions From Stationary Sources (Instrumental Analyzer Procedure)	O_2	Method 3A is a procedure for measuring oxygen (O_2) and carbon dioxide (CO_2) in stationary source emissions using a continuous instrumental analyzer.	https://www.epa.gov/ sites/production/files/ 2016-06/documents/ method3a.pdf
EPA 40 CFR 60 (A) Method 7E	Determination of Nitrogen Oxides Emissions From Stationary Sources (Instrumental Analyzer Procedure)	NO_x	Method 7E is a procedure for measuring nitrogen oxides (NO_x) in stationary source emissions using a continuous instrumental analyzer.	https://www.epa.gov/ sites/production/files/ 2016-06/documents/ method7e.pdf
EPA 40 CFR 60 (A) Method 10	Determination of Carbon Monoxide Emissions From Stationary Sources (Instrumental Analyzer Procedure)	CO	Method 10 is a procedure for measuring carbon monoxide (CO) in stationary source emissions using a continuous instrumental analyzer.	https://www.epa.gov/ sites/production/files/ 2016-06/documents/ method10r06.pdf
EPA 40 CFR 60 (A) Method TO-15	Determination of VOCs in Air using specially prepared canister with subsequent analysis by GC	Total VOC	Determination of toxic organic compounds in ambient air.	https://www3.epa.gov /ttnamti1/files/ambient/ airtox/to-15r.pdf
EPA 40 CFR 60 (A) Method 19	Determination of Sulfur Dioxide Removal Efficiency and Particulate Matter, Sulfur Dioxide, and Nitrogen Oxide Emission Rates	Exhaust Flow	The data is correlated with the fuel gas composition and the measured exhaust gas Oxygen content to arrive at the overall exhaust effluent flow.	https://www3.epa.gov/ ttnemc01/promgate/m-19.pdf

Table 2 EPA test methods accepted by BC

3.3. Saskatchewan

The Saskatchewan AQMS (Air Quality Management System) references Alberta and British Colombia methods and directives the Air Monitoring Guideline for Saskatchewan 16. The document references the following publications.

- Air Monitoring Directive, 1989, Prepared by Alberta Environment.
- AMD 2006, Amendments to the Air Monitoring Directive 1989, Prepared by Alberta Environment.
- British Columbia Field Sampling Manual, 2003, Prepared by B.C. Ministry of Water, Land and Air Protection.
- Methods and Procedures Document, 2006, Prepared by Greater Vancouver Regional District, Air Quality Policy and Management Division.
- Passive Air Sampling System, Technical and Instruction Information, Prepared by Maxxam Analytics Inc.
- Quality Assurance and Quality Control Guidelines, Report No. PMD 95-8, revised 2002, Environment Canada.
- Quality Assurance and Quality Control Guidelines, Report No. AAQD 2004-1, Environment Canada.
- United States Environmental Protection Agency (USEPA), 2008, QA Handbook for Air Pollution Measurement Systems, Volume II, Ambient Air Quality Monitoring Program.

3.4. Simplified test methods:

Simplified testing methods are not accepted by the federal regulator, ECCC (Environment and Climate Change Canada), for NO_x regulatory testing. Approval for any type of simplified test would require a variance or exception request. The request would have to be submitted and approved in advance of performing a simplified test.

3.5. Fleet and individual emission limits

MSAPR defines fleet average and individual engine emission limits. The limits change with time and if the engine is new or pre-existing. The units for the limits are expressed as follows.

- Emission component concentration is expressed as ppmvd @ 15% O_2 or ppmvd raw (uncorrected)
- Emission component intensity is expressed as g/kW/hr, g/kWh, g/kW-h, g/bhp-hr, g/bhp-h, tonnes/a, tonnes/yr or g/sec. We have adopted g/bhp-h and g/kW-hr for these reports.

The NO_x emission limits for individual engine are expressed as follows.

- MSAPR for Modern Engines: 160 ppmvd @ 15% O_2 (2.7 g/kW-hr)
- MSAPR for Pre-existing Engines: 210 ppmvd @ 15% O_2 (4 g/kW-hr)
- BCOGC (BC Oil and Gas Commission) for Rich Burn engines with a catalyst: 2.7 g/kW-hr

The NO_x emissions for the fleet average limits are presently defined as follows.

- MSAPR for Modern Engines: 160 ppmvd @ 15% O_2 (2.7 g/kW-hr)
- MSAPR for Pre-existing Engines until December 2025: 420 ppmvd @ 15% O_2 (8 g/kW-hr)
- MSAPR for Pre-existing Engines after January 2026: 210 ppmvd @ 15% O_2 (4 g/kW-hr)

The default NO_x emission values that may be adopted in lieu of testing for fleet management calculations are defined as follows.

- MSAPR for Pre-existing two stroke lean burn engines: 841 ppmvd @ 15% O_2 (16 g/kW-hr)
- MSAPR for Pre-existing four stroke lean burn engines: 710 ppmvd @ 15% O_2 (13.5 g/kW-hr)
- MSAPR for Pre-existing four stroke lean burn engines: 210 ppmvd @ 15% O_2 (4 g/kW-hr)
- MSAPR for Pre-existing rich burn engines: 1,262 ppmvd @ 15% O_2 (24 g/kW-hr)

3.6. Testing Protocol

All engines are required to be tested under the same test protocol regardless of combustion design. Emissions limits are dictated by the regulation and jurisdiction. The applicable protocol is determined by the regulation, permit or jurisdiction. Measurement devices and methods which may be are applicable are listed below.

- Electrochemical analyzers (ECOM, Testo),
- Evacuated vessel (Suma cannister or Tedlar bag) with Laboratory gas analysis,
- Continuous Emissions Monitoring System (CEMS) utilizing
  - instrumented analyzer (non-dispersive infrared: NDIR),
  - pneumatic magneto,
  - Fourier Transform Infrared Spectroscopy (FTIR),
  - gas chromatography-mass spectrometry (GC-MS),
  - Chemiluminescence (CL), and
  - Isokinetic sampling (Method 5 train)

The test protocols require testing to be carried with the engine operating at the highest achievable load that is greater than 90%. Each test run must be conducted while the engine is

(a) operating at the lower of

(i) 90% or more of its rated brake power, and

(ii) its highest achievable brake power for the operating conditions during the test run; and

(b) not operating during start-up, shutdown or a period of malfunction.

Engines that are operating at maximum speed and above 90% load will provide the most accurate representation of the emissions output. Testing engines at lower RPM and loads may not provide an accurate representation of the emissions output. Combustion efficiency is affected by engine speed and load. It is important to establish a baseline at max speed and load to ensure the integrity of the data. Site conditions will dictate the speed and power available at time of testing. Engine loads normally decrease over time unless production is maintained. Historical records are important to verify past and current operating conditions to prove the engine load conditions are consistent.

3.6.1. Challenges

- The ability to maintain a controlled test environment for the analysis equipment during testing with changes in test ambient conditions of extreme cold and heat.
- Obtaining stack access for sample port locations.
- Obtaining safe access to sample ports in extreme conditions (ambient temperatures, working at heights, hot exhaust component surfaces).
- Customer's limited knowledge of regulation and testing requirements, engine performance, engine tuning best practices, emissions chemistry, emissions controls and combustion theory.
- Managing equipment maintenance and calibration for CEMS and portable electrochemical analyzer, pumps, chiller, sample hose and supporting equipment.
- Maintaining a sufficient supply of calibration gas.
- Providing adequate capital or equipment and training.
- Sourcing, providing and training skilled testing resources.
- Limited reporting definition and standards.
- Providing adequate emissions testing services because a certification process is not required by the regulatory authorities.
- Managing regulations with a lack of flexibility for variances or exceptions. A revision or amendment process is not defined and the application process is lengthy.

3.6.2. Considerations for pre-chamber lean burn engines

3.6.2.1. Measurement locations

- Ensure sample ports are located in accordance with the applicable regulation (EPA M1, ASTM 6522D-11).
- Sample ports can be placed inside of building and tubed down to worker height.

3.6.2.2. Challenges

- Sample port quantity is doubled on a dual exhaust vs single exhaust configuration.
- Ensure air-fuel ratios are balanced on dual bank engines.
- Ensure access is provided by the package design and location of the exhaust sample port.
- Ensure crankcase ventilation system connection is downstream of the sample port to avoid affecting O_2 values and possible contamination of the testing equipment

3.6.2.3. Costs

- Twice the number of sample ports on dual exhaust configuration will require twice the number of tests and the associated cost increase.
- Sample ports located inside the building may eliminate the need for a manlift or scaffold and the associated cost increase for equipment and safety measures.
- Sample ports located outside the building or after the muffler will require access via manlift, scaffold or maintenance platform and the associated cost increase for equipment and safety measures.

- Adding insulation and heating an outdoor sample line for winter test conditions will increase testing cost.
- A mechanic trained on the engine management software may be required to tune the engine to compliance and work with the testing technician, doubling the manpower required to perform the emissions test and the associated cost.

3.6.2.4. Testing frequency

- Lean burn engines with greater than 75 kW rated power must undergo an initial performance test. An emission check must be performed within one year of the initial performance test. Ongoing testing applies for lean burn engines greater than or equal to 375 kW rated power. Performance tests are required at a frequency of every 17,520 hours or 36 months, whichever is less. Emissions tests are required every 12 months in between the performance tests.
- Compliance methods chosen affects the power threshold for testing and the engines to include in a testing program. Consult the MSAPR regulations for detailed information.
- A pre-chamber lean burn engine will emit approximately 10- 20 % less NO_x than a comparably equipped rich burn engine tuned to “best power” without catalyst.

3.6.3. Considerations for open chamber lean burn engines:

3.6.3.1. Measurement locations

- Ensure sample ports are located in accordance with the applicable regulation (EPA M1, ASTM 6522D-11).
- Sample ports can be placed inside of building and tubed down to worker height.

3.6.3.2. Challenges

- Sample port quantity is doubled on a dual exhaust vs single exhaust configuration.
- Ensure air-fuel ratios are balanced on dual bank engines.
- Ensure access is provided by the package design and location of the exhaust sample port.
- Ensure crankcase ventilation system connection is downstream of the sample port to avoid affecting O_2 values and possible contamination of the testing equipment

3.6.3.3. Costs

- Twice the number of sample ports on dual exhaust configuration will require twice the number of tests and the associated cost increase.
- Sample ports located inside the building may eliminate the need for a manlift or scaffold and the associated cost increase for equipment and safety measures.
- Sample ports located outside the building or after the muffler will require access via manlift, scaffold or maintenance platform and the associated cost increase for equipment and safety measures.
- Adding insulation and heating an outdoor sample line for winter test conditions will increase testing cost.
- A mechanic trained on the engine management software may be required to tune the engine to compliance and work with the testing technician, doubling the manpower required to perform the emissions test and the associated cost.

3.6.3.4. Testing Frequency

- Lean burn engines with greater than 75 kW rated power must undergo an initial performance test. An emission check must be performed within one year of the initial performance test. Ongoing testing applies for lean burn engines greater than or equal to 375 kW rated power. Performance tests are required at a frequency of every 17,520 hours or 36 months, whichever is less. Emissions tests are required every 12 months in between the performance tests.
- Compliance methods chosen affects the power threshold for testing and the engines to include in a testing program. Consult the MSAPR regulations for detailed information.
- A lean burn engine will emit approximately 10- 20 % less NO_x than a comparably equipped rich burn engine tuned to “best power” without a catalyst.

3.6.4. Considerations for stoichiometric engines without catalyst:

3.6.4.1. Measurement locations

- Ensure sample ports are located in accordance with the applicable regulation (EPA M1, ASTM 6522D-11).
- Sample ports can be placed inside of building and tubed down to worker height.

3.6.4.2. Challenges

- Sample port quantity is doubled on a dual exhaust vs single exhaust configuration.
- Ensure air-fuel ratios are balanced on dual bank engines.
- Ensure access is provided by the package design and location of the exhaust sample port.
- Ensure crankcase ventilation system connection is downstream of the sample port to avoid affecting O_2 values and possible contamination of the testing equipment

3.6.4.3. Costs

- Twice the number of sample ports on dual exhaust configuration will require twice the number of tests and the associated cost increase.
- Sample ports located inside the building may eliminate the need for a manlift or scaffold and the associated cost increase for equipment and safety measures.
- Sample ports located outside the building or after the muffler will require access via manlift, scaffold or maintenance platform and the associated cost increase for equipment and safety measures.
- Adding insulation and heating an outdoor sample line for winter test conditions will increase testing cost.
- A mechanic trained on the engine management software may be required to tune the engine to compliance and work with the testing technician, doubling the manpower required to perform the emissions test and the associated cost.

3.6.4.4. Testing frequency

- Rich burn engines with greater than 75 kW rated power must undergo an initial performance test. An emission test must be performed within 90 days of the initial performance test. Ongoing testing applies for rich burn engines greater than or equal to 375 kW rated power. Performance tests are required at a frequency of every 8,760 hours or 36 months, whichever is less. Emissions tests are required every 90 days in between the performance tests.

- An alternative performance testing frequency is specified as every 4,380 hours or 9 months, whichever is less. Emissions tests are not required with this performance testing frequency.
- Compliance methods chosen affects the power threshold for testing and the engines to include in a testing program. Consult the MSAPR regulations for detailed information.
- Rich burn engines emit the highest concentration of NO_x and the largest contribution of NO_x from stationery spark ignited reciprocating engines.

3.6.5. Considerations for stoichiometric engines with catalyst:

3.6.5.1. <u>Sensor reliability</u>

- Sensor reliability is dependent on location in the exhaust stream, engine health and engine load. Sensors have a shorter service life in higher temperature and higher gas velocity environments. Sensor failure and costs incurred unplanned shutdowns.
- NO_x and O_2 sensors have a reputation of short service life. Following the OEM and sensor manufacturer recommended service intervals will reduce the risk of unplanned shutdowns due to sensor failure.

3.6.5.2. <u>Catalyst performance</u>

- Monitor catalyst pre and post temperature to alert when temperatures are too high or too low for optimum catalyst performance.
- Monitor differential pressure measurement across the catalytic element to alert when the catalyst is becoming blocked
- Monitor the condition of the post catalyst NO_x sensor to alert when the sensor is drifting or the condition is deteriorating.
- Conduct regular emissions testing using a portable analyzer as part of routine engine maintenance to ensure the emissions control systems are operating and the engine condition remains sound.

3.6.5.3. <u>Measurement locations</u>

- Ensure sample ports are located in accordance with the applicable regulation (EPA M1, ASTM 6522D-11).
- Tubing from sample ports can be run inside the building and terminated with a valve at worker height and must be sampling exhaust downstream of the catalyst.

3.6.5.4. <u>Challenges</u>

- Sample port quantity is doubled on a dual exhaust vs single exhaust configuration.
- Ensure air-fuel ratios are balanced on dual bank engines.
- Ensure access is provided by the package design and location of the exhaust sample port.
- Ensure crankcase ventilation system connection is downstream of the sample port to avoid affecting O_2 values and possible contamination of the testing equipment.
- Ensure condensation in sample lines do not freeze in cold weather testing conditions.
- Ensure the catalyst element is sealed internally in the housing.
- The health of the catalyst is expected to change over time.

- Rich burn engines that are equipped with an air fuel ratio control system that is not adaptive are more likely to be out of tune. Operating the engine off the optimum design setting reduces both the engine performance and the catalyst service life.
- An engine operating in poor health or condition will reduce the catalyst service life.
- Deteriorated catalyst element condition will reduce engine health due to increased exhaust back pressure and exhaust temperature.
- Ensure the crankcase ventilation system connection is located downstream of the catalyst housing to prevent fouling of the catalyst element.

3.6.5.5. Costs

- More frequent tuning of the engine if not equipped with an adaptive AFR will contribute to increased operating costs.
- Maintenance of sealing and retention mechanisms for the catalyst housing will increase the operating costs compared engines that do not require a catalyst.
- Maintenance and replacement of the NO_x and O_2 sensors to maintain sound engine operating life
- The catalyst capital cost, maintenance cost and service life are dependent on the following aspects.
    - The initial quality specification of the catalyst and if it has a service life guarantee.
    - Stable engine operation supported by AFR system quality, equipment configuration and maintenance.
    - Sound engine health without blowby, glycol contamination or high exhaust temperature.
    - Location of the catalyst relative to the engine that will maintain optimum operating temperatures and pressures.
    - Location of the catalyst upstream of the crankcase ventilation system connection to avoid contamination of the catalyst.
    - Fuel gas quality that allows the engine to operate at normal exhaust temperatures and combustion in the catalyst that does not promote clogging.
- Twice the number of sample ports on dual exhaust configuration will require twice the number of tests and the associated cost increase.
- Sample ports located inside the building may eliminate the need for a manlift or scaffold and the associated cost increase for equipment and safety measures.
- Sample ports are located outside the building or after the muffler require access via manlift, scaffold or maintenance platform with the associated cost for equipment and safety measures.
- Adding insulation and heating an outdoor sample line for winter test conditions will increase testing cost.
- A mechanic trained on the engine management software may be required to tune the engine to compliance and work with the testing technician, doubling the manpower required to perform the emissions test and the associated cost.

3.6.5.6. Testing frequency

- Rich burn engines with greater than 75 kW rated power must undergo an initial performance test. An emission check must be performed within 90 days of the initial performance test. Ongoing testing applies for rich burn engines greater than or equal to 375 kW rated power. Performance tests are required at a frequency of every 8,760 hours or 36 months, whichever is less. Emissions tests are required every 90 days in between the performance tests.
- An alternative performance testing frequency is specified as every 4,380 hours or 9 months, whichever is less. Emissions tests are not required with this performance testing frequency.
- Compliance methods chosen affects the power threshold for testing and the engines to include in a testing program. Consult the MSAPR regulations for detailed information.
- Rich burn engines without a catalyst emit the highest concentration of NO_x and the largest contribution of NO_x from stationery spark ignited reciprocating engines. The addition of a catalyst will emit the lowest NO_x concentrations.

4. Best Management Practices for Testing

4.1. Instrument condition

- Perform spot checks on analyzers
  - ECOM
  - Testo electrochemical analyzer.
- Perform regulatory checks
  - Continuous Emissions Monitoring laboratory grade analyzers require a maximum 2% accuracy error tolerance.

4.2. Engine adjustment

- Engine timing and oxygen % setting to be set in accordance with OEM specifications.
- Engine with manual Air fuel Ratio control require consistent maintenance oversight and adjustment due to changing loads, fuel gas quality and atmospheric conditions.
- Air fuel ratio control (AFRC) with exhaust stream oxygen sensing will adjust to changing loads, fuel gas quality and atmospheric conditions. The AFRC will maintain a consistent air fuel ratio to achieve a pre set oxygen percent value resulting in a stable and emissions compliant operation.
- Components and supporting systems such as ignition systems, cooling systems, mechanical controls, and crankcase ventilation and fuel system require regular maintenance to ensure optimum engine health.

4.3. Engine condition

- A predictive maintenance program is recommended to maintain a high level of reliability and maximize service life.

The following conditions reduce engine health and performance.

- Excessive blowby.

- Internal coolant leaks.
- Improper Intake and exhaust valve lash settings.
- Worn intake and exhaust valves and seats.
- Defective ignition system.
- Incorrect timing.
- Incorrect air fuel ratio.
- Defective governor resulting unsteady or incorrect speed control.
- Loose or worn engine mechanical controls resulting in unsteady or incorrect engine operation.
- Fuel gas quality resulting in high combustion temperatures, high engine temperature, oil degradation, engine contamination or lagging performance.
- Poorly maintained coolant system thermostats, heat exchangers or eroded glycol quality resulting in inefficient cooling or operating at a temperature outside of design limits.
- Poorly maintained lube system using incorrect lubricant type, deteriorated oil condition, inefficient heat exchangers, incorrect oil pressure regulator setting and wrong oil temperature thermostat.
- Pre & post lubrication system either not provided or not working.

4.4. Least testing cost by installation

- Lean burn engines equipped with working height sample ports located inside the building.
- Capitalize on scale of economies with multiple Lean burn engines at one facility. all equipped with sample ports at working height inside the building.
- The following list defines the relative testing cost by engine type, from least to most expensive.
    - Lean burn: MSAPR pre-existing, annual test.
    - Lean burn: MSAPR modern, annual, stratification test.
    - Rich burn: MSAPR pre-existing, minimum 2 tests annually.
    - Rich burn: MSAPR modern, minimum 2 tests annually, stratification test.
    - Rich burn: MSAPR pre-existing (fixed set point controls), minimum 3 tests annually.

4.5. Suggestions for simplified engine testing

- Simplified testing requires preapproval from the regulator in advance of testing. A variance request may be considered or approved by the regulator if a simplified test can be justified. This would be at the discretion of the regulator. Approval would be required in advance of testing.
- Manage tests by group based on geography, engine type and weather during testing.
- Manage testing by area with multiple engines.
- Synchronize testing intervals between multiple engines.
- Manage testing to consider seasonal road conditions and accessibility.
- Manage testing to consider engine performance and ability to comply in hot ambient and high altitude applications.

4.6. Managing challenges

- Ensure engine readiness for testing with local maintenance staff performing emissions tests to confirm NO_x emission compliance is achieved in advance of the regulatory test.
- Ensure MSAPR compliant sampling ports are installed and sampling can be performed at worker height.
- Provide accessibility to sample ports via maintenance platforms or manlift.
- Adjust operating conditions to ensure engine load is within 10% of previous test.

APPENDIX A

Engines Models, Ignition Systems and Engine Management Systems

A1: List of Popular Engine Models and Combustion Styles

ACCURATA INC

Popular Engines Producing More Than 75 kW and their Combustion Styles and Report References

Engine Model	Report 2; Pre-chambered Lean Combustion Style	Report 3; Open Chamber Lean Combustion Style	Report 4; Rich Burn Combustion Style Without Catalyst	Report 4; Rich Burn Combustion Style With Catalyst
Pre-chambered Caterpillar 3600 A3 series	x			
Pre-chambered Caterpillar 3600 A4 series	x			
Open chambered rich burn Caterpillar 3500 TA series			x	
Open chambered lean burn Caterpillar 3500 TALE series		x		
Open chambered lean burn Caterpillar 3500 A3 series		x		
Open chambered lean burn Caterpillar 3500 J series		x		
Open chambered stoichiometric Caterpillar 3400 TA series			x	x
Open chambered lean burn Caterpillar 3400C LE series		x		
Open chambered rich burn Caterpillar CG137 ADEM 4				x
Open chambered rich burn Caterpillar G3300B ADEM 4				x
Pre-chambered Waukesha VHP GL	x			
Open chambered stoichiometric Waukesha VHP GSI			x	x
Open chambered lean burn Waukesha VHP LT		x		
Open chambered stoichiometric Waukesha VHP G			x	x
Open chambered stoichiometric Waukesha VHP GSI series 4			x	
Open chambered stoichiometric with Catalyst Waukesha VHP GSI series 4 AFR2				x
Open chambered stoichiometric with Catalyst Waukesha VHP GSI series 5 AFR2				x
Pre-chambered Waukesha AT GL	x			
Open chambered stoichiometric Waukesha VGF GSI series			x	
Open chambered lean burn Waukesha VGF GL series		x		
Open chambered stoichiometric White G-825			x	x
Open chambered rich burn White GTL-825			x	
Open chambered stoichiometric White SGT-825			x	
Pre-chambered lean burn White GTLA-825	x			
Pre-chambered lean White GTLB-825	x			

A2: List of Engine Management Systems and Combustion Styles

Engine Management System Applications

Engine Management System	Pre-chamber Lean Burn Combustion Style	Open chamber Lean Burn Combustion Style	Rich Burn Combustion Style Without Catalyst	Rich Burn Combustion Style With Catalyst
Vortex VETS (NSCR Catalyst equipped)				x
Spartan REACTT rich burn (NSCR Catalyst equipped or without)			x	x
Spartan REACTT lean burn (open chamber lean burn)		x		
Spartan REMVue (NSCR Catalyst equipped or without)			x	x
Spartan REMVue lean burn (pre-chambered lean burn controller)	x			
Spartan REMVue lean burn (open chamber lean burn controller)		x		
Caterpillar ADEM 3 (open chamber lean burn)		x		
Caterpillar ADEM 3 (pre-chambered lean burn)	x			
Caterpillar ADEM 4 (pre-chambered lean burn)	x			
Waukesha ESM AFR (NSCR Catalyst equipped or without)			x	x
Waukesha ESM AFR (pre-chambered lean burn)	x			
Waukesha ESM AFR (open chamber lean burn)		x		
Waukesha ESM 2 AFR 2 (NSCR Catalyst equipped)				x
Waukesha ESM 2 (pre-chambered lean burn)	x			
Waukesha Legacy CEC (open chamber rich burn)			x	
Caterpillar legacy G3500 series EMS (open chamber lean burn)		x		
Caterpillar legacy G3500 series EMS (open chamber rich burn)			x	x
Caterpillar CDIC G3400TA (open chamber rich burn)			x	x
Waukesha LT (CEC + air fuel module)		x		
White Superior Clean Burn (pre-chambered lean burn)	x			
Cooper Control System (White Superior)			X	X

A3: List of Ignition and Engine Management System Models

Ignition Systems Included in These Reports
Manuafacturer and Model
Caterpillar Magneto
Caterpillar DIS
Caterpiular EIS
Altronic CPU 95
Altronic-III
Altronic DISN 800 (Same as Waukesha CEC)
Murphy MPI
Murphy Intellispark

Engine Management Systems Included in These Reports
Manuafacturer and Model
Waukesha ESM
Waukesha ESM2
Caterpillar ADEM 3
Caterpillar ADEM 4
Altronic AFR 500 (NSCR Catalyst equipped)

Rich Burn Engine Management Systems Excluded From Consideration
Manuafacturer and Model
Motortech Emcom 5
Woodward E3 rich burn control
Altronic EPC 50 (NSCR Catalyst equipped)
Altronic EPC 100 (NSCR Catalyst equipped)
Waukesha ESM AFR 2 (NSCR Catalyst equipped)
Caterpillar ADEM 4 (stoichiometric)

Unpopular Ignition Systems Excluded From Consideration
Manuafacturer and Model
Altronic CPU 2000
Altronic CPU XL
Motortech MIC3+
Motortech MIC4
Motortech MIC4ZS
Motortech MIC5
Motortech MIC6
Altronic I, V
Altronic CD 200

A4: List of Engine Models contributing less than 5% of the Alberta Fleet and small engines less than 75 kW

Engines that comprise less than 5% of the Alberta fleet (unpopular engines plus small engines less than 75 kW)

Engine Model	Trunk Compressor	2 stroke	Engine Model	Trunk Compressor	2 stroke
Admiralty ASR-1-16VMS			Cooper-Bessemer GMXE-6	x	x
Ajax DPC series	x	x	Cooper-Bessemer GMXF-10	x	x
Ajax SB series	x	x	Cooper-Bessemer GMXH series	x	x
Ariel JGS series	x		Cooper-Bessemer GMXH-12	x	x
Arrow VRG 220 (NA)			Cooper-Bessemer GNG series	x	
Arrow VRG 330NA			Cooper-Bessemer GSB-8	x	
Arrow VRG 330TA			Cooper-Bessemer Hope	x	
Caterpillar 3400 NA series			Cooper-Bessemer JS	x	
Caterpillar 3400 TALE series			Cooper-Bessemer JSG-5	x	
Caterpillar 3500 B series (discontinued)			Cooper-Bessemer JSG-6	x	
Caterpillar G-300 series			Cooper-Bessemer KSV series	x	
Caterpillar G3300 NA series			Cooper-Bessemer LSV	x	
Caterpillar G3300 TA series			Cooper-Bessemer LSV-12	x	
Caterpillar G3520 LE			Cooper-Bessemer QUAD series	x	x
Caterpillar GCM series			Cooper-Bessemer TYPE-26	x	
Caterpillar MWM series			Cummins B6.7N (TA)		
Chicago-Pneumatic CPG series	x		Cummins G series		
Chicago-Pneumatic RHG-B-50V	x		Cummins GTA series		
Clark BA-8	x	x	Cummins KTA		
Clark HBA series	x	x	Cummins L9N (TA)		
Clark HLA series	x	x	Delaval-Enterprise DSRV-16-4		
Clark HMA series	x	x	Delaval-Enterprise HVA-8C2		
Clark HMB-8	x	x	Fairbanks-Morse OP or MEP series		x
Clark HSRA series	x	x	Ingersoll-Rand FTKUS-48	x	
Clark RA series	x	x	Ingersoll-Rand JVG series	x	
Clark RAS series	x	x	Ingersoll-Rand KVG series	x	
Clark TCV series	x	x	Ingersoll-Rand KVGR series	x	
Clark TCVC series	x	x	Ingersoll-Rand KVR-38	x	
Clark TCVD-10	x	x	Ingersoll-Rand KVS series	x	
Clark TLA series	x	x	Ingersoll-Rand KVSB-412	x	
Clark TLAD-8	x	x	Ingersoll-Rand KVSR series	x	
Clark TLA-S-10	x	x	Ingersoll-Rand KVSRA series	x	
Clark TMB-10	x	x	Ingersoll-Rand KVSRB-412	x	
Clark TRA-6M	x	x	Ingersoll-Rand KVT series	x	
Cooper-Bessemer 10W-330	x	x	Ingersoll-Rand LVG-8	x	
Cooper-Bessemer 10Z-330	x	x	Ingersoll-Rand PJVG series	x	
Cooper-Bessemer 12/14V-250	x	x	Ingersoll-Rand PKVG series	x	
Cooper-Bessemer 12V-250	x	x	Ingersoll-Rand PSVG series	x	
Cooper-Bessemer 12W-330	x	x	Ingersoll-Rand PVG series	x	
Cooper-Bessemer 12W-330C2	x	x	Ingersoll-Rand SVG series	x	
Cooper-Bessemer 14W-330	x	x	Ingersoll-Rand TVR series	x	
Cooper-Bessemer 16V-275	x	x	Ingersoll-Rand TVS-612	x	
Cooper-Bessemer 16W-330	x	x	Ingersoll-Rand XVG series	x	
Cooper-Bessemer 16Z-330	x	x	Jennbacher J208		
Cooper-Bessemer 22- Natural- Aspirated	x		Jennbacher J300 series		
Cooper-Bessemer 22-Turbocharged	x		Jennbacher J400 series		
Cooper-Bessemer 24/36TC	x		Jennbacher J600 series		
Cooper-Bessemer 24-Turbocharged	x		Superior 2400 serries		
Cooper-Bessemer 8V-275	x	x	Wartsila		
Cooper-Bessemer GMV series	x	x	Waukesha 275 GL series		
Cooper-Bessemer GMVA series	x	x	Waukesha ATGL series		
Cooper-Bessemer GMVA-4	x	x	Waukesha VRG series		
Cooper-Bessemer GMVC series	x	x	Waukesha VSG GL series		
Cooper-Bessemer GMVE-12	x	x	Waukesha VSG GSI series		
Cooper-Bessemer GMVG-10	x	x	Worthington BBG-6	x	
Cooper-Bessemer GMVS-10	x	x	Worthington BG-6	x	
Cooper-Bessemer GMW series	x	x	Worthington CCG-6		
Cooper-Bessemer GMWA series	x	x	Worthington LTC-8		x
Cooper-Bessemer GMWC series	x	x	Worthington ML series	x	x
Cooper-Bessemer GMWS-10	x	x	Worthington MLV series		x
Cooper-Bessemer GMX series	x	x	Worthington SEHG-6		
Cooper-Bessemer GMXA-6	x	x	Worthington SLHC series	x	
Cooper-Bessemer GMXA-6	x	x	Worthington SLHP-5	x	
Cooper-Bessemer GMXD series	x	x	Worthington SUTC series	x	x
Cooper-Bessemer GMXE series	x	x	Worthington UTC series		x

A5: Estimated Population of Engines in Western Canada by Make and Model

Popular engines > 100 HP included in the report	Percent of Alberta Fleet.
Pre-chambered Cat 3600 A3 series	6.7%
Pre-chambered Cat 3600 A4 series	3.4%
Open chambered rich burn Cat 3500 TA series	7.7%
Open chambered lean burn Cat 3500 TALE series	8.2%
Open chambered lean burn Cat 3500 A3 series	5.3%
Open chambered lean burn Cat 3500 J series	0.5%
Open chambered stoichiometric Cat 3400 TA series	8.1%
Open chambered lean burn Cat 3400C LE series	1.4%
Open chambered lean burn Cat CG137 ADEM 4	0.5%
Open chambered stoichiometric CAT G3300B ADEM 4	1.9%
Pre-chambered Waukesha VHP GL	9.6%
Open chambered stoichiometric Waukesha VHP GSI	2.4%
Open chambered stoichiometric with catalyst Waukesha VHP GSI	2.4%
Open chambered lean burn Waukesha VHP LT	1.7%
Open chambered stoichiometric Waukesha VHP G	4.8%
Open chambered stoichiometric with catalyst Waukesha VHP G	1.7%
Open chambered stoichiometric Waukesha VHP GSI series 4	12.0%
Open chambered stoichiometric with catalyst Waukesha VHP GSI series 4 AFR2	1.9%
Open chambered stoichiometric with catalyst Waukesha VHP GSI series 5 AFR2	1.9%
Pre-chambered Waukesha AT GL	0.7%
Open chambered stoichiometric Waukesha VGF GSI series	2.4%
Open chambered lean burn Waukesha VGF GL series	1.9%
Open chambered stoichiometric White G-825	2.7%
Open chambered stoichiometric with catalyst White G-825	1.0%
Open chambered lean burn White GTL-825	3.0%
Open chambered stoichiometric White SGT-825	0.3%
Open chambered stoichiometric with catalyst White SGT-825	0.3%
Open chamber lean burn White GTLA-825	0.2%
Open chamber lean White GTLB-825	0.2%
Open chamber lean burn stoichiometric White GTLE-825	0.2%

Waukesha and Caterpillar each have approximately 46% of the engine population, White-Superior approximately 8%. This only accounts for engines considered in the scope of the study and does not account for the entire engine population in Western Canada. The remaining engines are out of scope and account for approximately 5% of the total engine population above 100hp. The above numbers are best effort estimates as of mid 2022, as an accurate count is not available.

APPENDIX B

Ignition System and Engine Management System Capabilities

B1: TABLES OF IGNITION AND ENGINE MANAGEMENT SYSTEMS WITH CAPABILITIES

Aftermarket ignition systems:

Ignition Systems						
		Altronic			Murphy	
		CPU 95	III	DISN 800	MPI	Intellispark
Engine Models						
Description						
CSA Certification		Y	Y	Y	Y	Y
Timing Adjustment	Auto	Y	N	Y	Y	Y
	Manual	Y	Y	Y	Y	Y
Speed Control	Auto	N	N	N	N	N
	Manual	N	N	N	N	N
Governor Deviation		N	N	N	N	N
Flame front monitoring (part of EMS)		N	N	N	N	N
Detonation monitoring		N	N	N	N	N
Pyrometer (part of EMS)		N	N	N	N	N
Integration with EMS		N	N	N	N	N

OEM Engine Management systems:

OEM Ignition Systems								
		Waukesha		Caterpillar				
		ESM	ESM2	Magneto	DIS	EIS	ADEM A3	ADEM A4
Engine Models		VHP;VGF,AT	VHP; 275GL+	G3300	G3400	G3400CLE-G3500	G3500-3600	G3300,3600, CG137
Description		IPM	IPM2	Solid State	Digital	Electronic	Advanced	Advanced
CSA Certification		y	y	Y	Y	Y	Y	Y
Timing Adjustment	Auto	y	y	N	N	Y	Y	Y
	Manual	Dual fuel	N	Y	Y	N	N	N
Speed Control	Auto	Y	Y	N	N	Y	Y	Y
	Manual	Y	Y	Y	Y	N	N	N
Power Sourse		24VDC	24VDC	Self	12 or 24VDC	24VDC	24VDC	24VDC
Flame front monitoring (part of EMS)		N	y	N	N	N	Y	Y
Detonation monitoring		Y	Y	N	N	Y	Y	Y
Pyrometer (part of EMS)		Y	Y	N	N	Y	Y	Y
Integration with EMS		ESM	ESM2	Instrument Panel	DIS Module	EIS Control Module	ADEM A3	ADEM A4

APPENDIX C

Engine model history

C1: WAUKESHA, CATERPILLAR AND WHITE-SUPERIOR ENGINE MODEL HISTORY

Waukesha engine history:

-1963 7040 introduced.

-1967 VHP series introduced: F3521, L5790, L7042.

-1969 P9390 introduced.

-1974 Dresser acquired Waukesha.

-1977 Increased VHP speed to 1200 rpm.

-1981 Obtains licenses from Sulzer to build AT series.

-1985 GL series of lean burn VHP engines introduced.

-1985 ATGL introduced

-1988 VGF GL introduced

-1998 Improved GSI engines introduced as Series 4: 3524 GSI and 7044 GSI

-1998 AT27GL introduced

-2001 ESM introduced.

-2000 5794LT introduced

-2001 5774LT introduced specifically for gas compression markets

-2010 GE acquired Dresser, including Waukesha.

-2018 GE sells Waukesha to Advent International, branded as Innio.

Caterpillar engine history:

-1974 3400 series diesel engines introduced.

-1978 G3306 introduced.

-1981 3500 series diesel engine introduced.

-1985 G3500 series gas engines introduced.

-1985 G3400 series gas engines introduced.

-1985 G3600 series introduced as diesel engines.

-1991 G3606 series gas engines introduced for compression service.

-1991-1994 G3608, G3612 and G3616 introduced.

-1995 Low emission G3408C and 3412C introduced.

-2000 ADEM 3 control system introduced.

- 2002 G3520 introduced.

White-Superior Engine history:

-1959 G825 series introduced, 6 and 8 cylinder inline

-1963 12 and 16 cylinder V variants of the G825 introduced.

-1975 SGT turbocharged high output engines introduced.

-1980's Cleanburn I and II developed

-1997 Cleanburn III processor controlled engine management introduced.